THE ROLE OF AUTOMATED WEATHER NETWORKS IN PROVIDING EVAPOTRANSPIRATION ESTIMATES

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ABSTRACT

In the U.S., automated weather networks have grown rapidly in number and extent. One important application of real-time weather data is the estimation of evapotranspiration (ET) from crops and/or landscapes. Networks use various approaches for collecting, transmitting, and quality assuring the "raw" weather data, and for calculating, packaging, and disseminating ET information. When incorporated into an irrigation scheduling program, this information can lead to significant improvements in water management.
KEYWORDS. Automated weather network, Evapotranspiration, Irrigation scheduling, Irrigation water management.

AUTOMATED WEATHER NETWORKS

Scope

Advances in electronic instruments and the desire for timely (at least daily and often in real-time) weather information have led to considerable growth in the number of automated weather stations. In a survey conducted in 1991, Meyer and Hubbard (1992) identified 831 stationary automated weather stations operating in the U.S. and Canada. A follow-up survey (Hubbard and Brusberg, 1999) found more than 1200 stations. These stations are in addition to the Automated Surface Observation Stations (ASOS) of the National Weather Service (NWS) which are located near airports and serve aviation and forecasting needs, and the NWS Cooperative Station Network which is staffed primarily by volunteers who take a limited set of daily measurements.

Most automated weather stations are a part of networks that cover geographic areas ranging in size from a few counties to a multi-state region. These networks are typically operated by land-grant universities or government agencies. The Hubbard and Brusberg (1999) survey identified 37 automated networks, half of which were initiated in the past ten years. Agriculture is the primary focus of many of these networks and at least of secondary interest for most others, based on responses to the survey question "What factors determine the location of a new station?" Since the majority of automated stations measure temperature, humidity, solar radiation, and wind, physically-based estimates of evapotranspiration (ET) can be generated and are available from many networks. These ET estimates, and associated information products, are used to support and improve irrigation water management in both agricultural and urban settings.

No two networks are alike, and it is a challenge to summarize the features of all those which provide ET estimates. Included in this paper are some general observations, along with more

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specific information for those networks with which the authors are most familiar. No attempt has been made to provide an exhaustive review of U.S. networks.

Station Siting

A weather station's environment can significantly influence the physical measurements that are used in ET calculations. The characteristics and extent of the upwind surface, i.e., the fetch, affect the near-surface atmosphere that is monitored by the weather station. All else being equal, a station in a non-irrigated environment will measure higher temperatures and lower humidities than a station that is surrounded by an adequate expanse of well-watered vegetation (Allen, 1996). The magnitude of this difference tends to increase as the aridity of the region increases. Also, obstructions or other non-uniformities in surface roughness can affect boundary-layer aerodynamics and the associated wind speeds measured at the weather station. A site surrounded by tall annual crops will experience reduced wind speeds as the season progresses.

When ET is estimated for irrigation management purposes, typically a *reference* ET value is multiplied by a crop coefficient to yield *actual* ET. The reference crop is either grass or alfalfa, and the empirically determined crop coefficients should be tied not only to the specific reference crop (i.e., grass or alfalfa), but also to the condition of that reference surface. FAO Irrigation Drainage Paper 56 (Allen et al., 1998) describes the (grass) reference surface as closely resembling "an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water. The requirements that the grass surface should be extensive and uniform result from the assumption that all fluxes are one-dimensional upwards."

For the purposes of ET estimation for irrigation, a weather station should ideally be sited in an environment similar to that described above. However, for most networks, this ideal is precluded by the logistics of maintaining an extensive, uniform, well-watered surface. Even for those sites where irrigation water is available, and where the vegetation can be frequently clipped, rarely can this type of surface be maintained over the entire fetch that influences the weather station. Furthermore, for multi-purpose weather networks, a classic reference-ET station may provide measurements that are not representative or appropriate for other applications. As one example, "artificially" elevated dewpoint temperatures and depressed air temperatures may provide misleading information to a weather forecaster. Hubbard and Brusberg (1999) indicated that 55 percent of automated weather station sites have a "natural" cover, with 25% grass, 1% alfalfa, and 19% other. Information is not available on the prevalence of irrigation at the grass sites. It should be pointed out that, because of the importance of irrigation scheduling for lawns and parks, some networks have stations sited in urban environments. Siting criteria for the California Irrigation Management Information System (CIMIS) are available online (California Department of Water Resources, 1998).

Data Collection and Transmission

An automated weather station typically has an array of sensors mounted on or near a tower, tripod, or mast. An on-site datalogger polls the sensors at regular intervals, converts the sensor readings as necessary, does some rudimentary data processing (calculating means, maxima, minima, etc.), and stores the resulting data. Most stations are battery-powered and use a solar panel to maintain battery charge. The ASAE Irrigation Management Committee (SW-244) has been engaged in the development of an engineering practice for measurement and reporting procedures for agricultural weather stations (Yoder et al., 2000).

Networks use various means to collect or transmit the data stored in the dataloggers. Methods include (Hubbard and Brusberg, 1999): (a) site visits by technicians (used by 15% of the networks responding to the survey), (b) telephone land-lines (67%), (c) cellular telephone (37%), (d) line-of-site radio telemetry (20%), and (e) satellite transmission (7%). The percentages sum to greater than 100% because a number of networks use a combination of methods to transmit data. Other data transfer technologies in use include meteor-burst radio frequency communication, internet file transfer protocol (FTP), and spread-spectrum radio. The frequency at which data are transmitted from the remote weather station to the network's central processing facility ranges from fifteen minutes to one day.

Data Quality Assurance

The quality of ET estimates is of course dependent upon the quality of the weather data that are used in the calculations. A comprehensive quality-assurance program should encompass instrument calibration, maintenance, repair, and replacement; field deployment and site maintenance issues; and data checks via automated computer routines as well as visual inspection (Shafer et al., 2000).

The types of instrumentation and the operational budgets vary greatly among the networks (Hubbard and Brusberg, 1999), so differences in the calibration procedures would be expected. A few networks indicated that "pre-release" calibration is performed. In other words, instruments are checked for accuracy immediately upon delivery from the manufacturer and before they are installed at weather stations. After deployment in the field, sensors are periodically rotated out of service so that they can be re-calibrated. This is done either on a fixed schedule, or when a field intercomparison suggests that a sensor is in need of re-calibration. Most networks perform their own calibration, but in some cases the sensors are shipped back to the manufacturer or some other vendor.

According to the results of the Hubbard and Brusberg (1999) survey, the response time for repairing or replacing a malfunctioning instrument ranges from 0 to 120 days, with an average of about 18 days. Just over 60 percent of the networks surveyed perform their own maintenance and field visits, with the rest contracted out to other parties.

The rigor used in assuring the quality of weather data varies from network to network. Surprisingly, over 10% of the survey respondents reported that no action is taken when erroneous data are identified. In contrast, over 80 percent of the networks make some attempt to correct data errors, and about 20 percent flag suspect values whether they are corrected or not.

Those networks that are active in quality assurance reported having up to 12 employees working on one or more aspects of this issue, with an average of 2.5 amongst all respondents. Only about 20 percent of the networks, however, have staff dedicated to quality assurance on a full-time basis. Personnel resources for network operation and maintenance are often constrained by a lack of funding.

EVAPOTRANSPIRATION AND IRRIGATION SCHEDULING INFORMATION

Calculations

As mentioned previously, the reference-ET/crop-coefficient approach is employed nearly universally for operational estimates of crop or turf evapotranspiration. However the uniformity among networks is not as great as it may first seem, because there are many different methods for calculating reference ET, as well as various sets of crop coefficients.

The California Irrigation Management Information System (CIMIS) (California Department of Water Resources, 1999) and The Arizona Meteorological Network (AZMET) (Brown, online) calculate *hourly* grass reference ET (ET_{oh}) using a version of Penman's equation (Snyder and Pruitt, 1992). The equation requires inputs of hourly air temperature, wind speed (2 m height), vapor pressure, and solar radiation. AZMET wind speeds are measured at a height of 3 m and are adjusted to 2 m using the standard power law equation; CIMIS anemometers are deployed at a height of 2 m. The only other significant difference between the CIMIS and AZMET ET_o

procedures is in the computation of net radiation (an important parameter in the ET computation). CIMIS follows the procedure of Dong et al. (1992), and AZMET employs a relatively simple clear sky procedure.

The North Plains PET Network (NPPET) (Marek and Marek, online) in the Texas Panhandle computes daily potential (grass reference) ET using the Penman-Monteith equation (Allen et al., 1994). The grass reference was chosen because urban clientele could, perhaps, more easily understand it. NPPET uses growing-degree-days as the thermal time parameter for computing crop coefficients and for estimating crop development rates. The crop coefficients were developed from USDA-ARS research, and they represent "mean" values (i.e., they are generic to the region rather than specific to a given farm or field). The NPPET is described in Marek et al. (1996). Texas has two other PET networks that use similar methods (Texas Agricultural Extension Service, online; Texas A&M Agricultural Research & Extension Center, online).

The Automated Weather Data Network (AWDN) (Hubbard et al., 1983), which is operated by a consortium of states in the northern part of the High Plains, computes the Penman combination equation (Kincaid and Heermann,1974) with the wind function representative of a reference alfalfa crop with full canopy. Growing degree days (GDD) are used as the thermal unit of time and accumulations of GDD are tagged to phenological progress and the coefficients for specific crops. The crop coefficients in the High Plains Regional Climate Center calculations of ET are based on the results of Nebraska studies (Hinkle et al., 1984) and other studies (Wright, 1982) adapted to conditions in the High Plains region.

The Washington Public Agricultural Weather System (PAWS) (Washington State University, online) calculates ET for an alfalfa reference using the 1982 Kimberly Penman equation (Wright, 1982), and for a grass reference using the FAO-24 approach (Doorenbos and Pruitt, 1977). An on-line ET calculator is available as an interactive tool that allows the user to see the influence of various inputs on the calculated ET value. The Bureau of Reclamation AgriMet program (U.S. Bureau of Reclamation, online) also provides crop water use information for Washington and other states in the Pacific Northwest.

As one of its agricultural applications (Oklahoma Cooperative Extension Service, online), the Oklahoma Mesonet (Brock et al., 1995) computes Penman-Monteith daily grass reference ET (Allen et al., 1994). That reference value is also scaled to derive daily values for alfalfa reference ET, cool-season grass ET (e.g., a fescue lawn), warm-season grass ET (e.g., a bermudagrass lawn), and pan evaporation. Details of the calculations are available online (Oklahoma Cooperative Extension Service).

As detailed in Walter et al. (2000), the ASCE Evapotranspiration in Irrigation and Hydrology Committee has recently endorsed the adoption of standardized reference evapotranspiration equations, one for a "short" (grass) reference (ET_{os}), and the other for a "tall" (alfalfa) reference (ET_{rs}). These equations represent simplified versions of the ASCE Penman-Monteith equation (Jensen et al., 1990), and can be used on either a daily or hourly time step. The goals of the standardization initiative are to reduce the confusion associated with the many reference ET equations that have been developed, to facilitate the comparison of evaporative demands in various climates, and to simplify the transfer of crop and landscape coefficients from one region to another. It is hoped that networks will consider the adoption of the ET_{os}/ET_{rs} approach to calculating reference ET.

Dissemination

Weather measurements, and the value-added information derived from those measurements, have the greatest value when they can be delivered to end-users in an efficient and timely manner. About three-fourths of the networks surveyed by Hubbard and Brusberg (1999) disseminate information to the public in a form for operational use. In some cases, this is done on a fee basis to defray operating expenses. Among those networks that do provide information to the public for operational use, about 85 % utilize the Internet for delivery, over 40% use ftp and/or fax, and about 25% use mail and/or telephone.

Some automated weather networks were instituted with ET and irrigation management information as the primary focus (e.g., CIMIS, NPPET). For other networks (e.g., PAWS, Oklahoma Mesonet), the most popular products may be associated with other agricultural (or non-agricultural) applications of weather data. In any case, the dissemination of ET and irrigation scheduling information can play a key role in helping to improve water management in crop and landscape irrigation.

The primary application of CIMIS is to provide information for improving water and energy management through efficient irrigation practices. Access to that information is available though telnet (via telephone modem or Internet link) and through an Internet home page.. The CIMIS Web site enables the user to select the station(s) of interest and download daily data from the last seven days, or monthly data from the preceding twelve months. This tabular information includes calculated ET_0 as well as various weather parameters. In the case of missing data, an historical average ET_0 is substituted for the calculated value. The Web site also has extensive statewide data on "normal year" ET_0, instructional information related to crop coefficients and water-budget irrigation scheduling, and lists of irrigation scheduling consultants and software. CIMIS has gone to considerable effort to compile (and develop) crop coefficients for many trees, vines, agronomic crops, grasses, landscapes, and vegetable crops. A 1995 survey conducted by the University of California at Berkeley found that, on average, farms using CIMIS to schedule irrigation experienced an 8-percent yield increase and a 13-percent reduction in water use. Economic benefits ranged from $99 per hectare for alfalfa to $927 per hectare for lettuce (California Department of Water Resources, 1997).

AZMET ET_0 and associated weather data are readily available on the Web. The data are summarized in a variety of formats, including several ready-to-use summaries that use English units, and comma-delimited ASCII text files that can be imported into most database and spreadsheet programs. A variety of tables is created. Special reports generated by AZMET include the Phoenix Area Turf Water Use Report that summarizes estimated lawn ET for the past 1, 3, and 7 days, and recommends an irrigation application amount (assuming no rainfall has occurred during the intervening period).

The NPPET network prepares a daily fax sheet containing values of PET, growing degree days, and crop water use for corn, cotton, wheat, sorghum, soybean, and peanut. This is done for each weather station (not all stations serve the full complement of crops listed above). Before 7:00 a.m. each day, NPPET computers fax the relevant sheet(s) to each subscriber and to media outlets. The approximately 350 subscribers in 1999 can be categorized as agribusiness (35%), producers (30%), government (25%), consultants (6%), and media (4%). Because of information sharing and dissemination, there is a "multiplier effect" with agribusiness, consultants, and the media. More than 125,000 faxes were sent out by the NPPET during 1999, and it is estimated that over 95% of those were successfully received. The same files, as well as the hourly weather data files, are also uploaded to a Web server for Internet access (Marek and Marek, online). In October of 1999, the NPPET Web page experienced over 134,000 "hits" and more than 11,000 pages were downloaded. It is estimated that the NPPET has an impact on at least 350,000 to 400,000 acres of irrigated crops, with projected savings in pumping costs of $5 million or more. In the urban arena, the ET data are routinely used to compute lawn water use for the Water Smart project in Amarillo/Canyon. Water use rates for three types of grasses are printed daily (May through November) in the Amarillo newspaper, and are reported on agricultural radio programs and weathercasts on Amarillo television.

The High Plains Regional Climate Center (online) disseminates data including near-real-time maps from the AWDN on a Web page and via an on-line, interactive Web system. Web site hits range between 150,000 and 200,000 per month, with the majority coming from the agricultural sector and a large number of these coming from farmers who irrigate or consultants who recommend irrigation schedules to their clients. The on-line system allows clientele to choose the crops, planting dates, and maturity groups that they wish to track. Summaries available include weekly summaries and seasonal summaries from emergence to date. The auto-pilot feature is a very popular and cost-cutting feature. It allows users to specify the desired report(s) they wish to receive daily by e-mail. Once specified, the client need not log on each day and re-enter the crops, etc. that are of interest. Instead, he/she automatically receives the report(s) at about 8:00 a.m. each day.

The PAWS network covers most of the irrigated regions of Washington. ET and weather information is available to subscribers via a Web interface. The Washington Irrigation Scheduling Expert (WISE) (Washington State University, online) is a Java-based application available as an irrigation scheduling and educational tool. Over 300 individuals have registered to access PAWS via computer. Approximately half of these use the system regularly, and the majority are consultants and crop advisors who themselves serve a large clientele. PAWS received about 50,000 data requests in 1999, about 7% of which were specifically targeted at ET, crop water use, and irrigation scheduling products. About one-fourth of the total requests were for raw data, and an additional one-fourth were for disease/insect model applications. Data dissemination also occurs through newspapers and radio stations and the older BBS system. There is also a voice-reporting system that allows free access to current weather information only. PAWS/WISE accommodates over 40 different crops and allows user input of emergence and harvest dates. Scientific irrigation scheduling demonstrations were conducted over a four-year period on over 60 farms in south central WA using PAWS weather and evapotranspiration data. The results showed that a minimum water savings (and pumping cost savings) of 10% compared to traditional practices could easily be achieved. This improved irrigation water management also brings benefits to basin-level water quantity and quality. A recent development is for the PAWS network to provide ET information to an automated, variable-rate irrigation system via a cell modem or embedded controllers.

Although not in a state with a large irrigated area, the Oklahoma Mesonet includes the "Oklahoma Evapotranspiration Model" (Oklahoma Cooperative Extension Service, online) on its AgWeather home page. This site provides tabular ET estimates for a user-selected station for the past 1, 7, 14, and 30 days. Another table lists yesterday's ET values for all stations in the network. Also available are printable forms for lawn irrigation scheduling, along with example calculations. Faxes and telephone answering machines have been used to disseminate water use information for peanuts (Kizer and Carlson, 1996). A web-based "Interactive Evapotranspiration Estimator" is being developed. This irrigation scheduling tool will incorporate crop coefficients and accumulate ET estimates over user-specified time periods.

CONCLUDING THOUGHTS

As the competition for water increases, and irrigators face economic and environmental pressures, improvements in water management are needed. Weather-based estimates of ET are a critical element of scientific approaches to irrigation scheduling. Hubbard and Brusberg (1999) identified a number of challenges facing network managers. These include maintaining a quality system, data collection standards, calibration standards, data exchange formats, operational funding, quality control of data, network coordination, technology upgrades, data access, and meeting constituents' needs. The value of ET and irrigation scheduling information should provide a strong impetus for effectively meeting these challenges.

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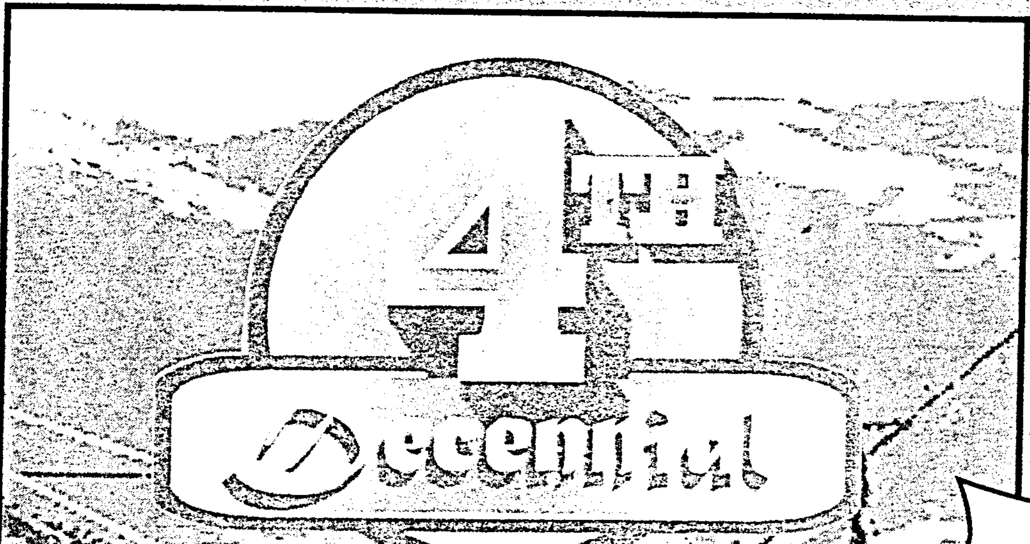

NOVEMBER 14-16, 2000
PHOENIX, ARIZONA

Proceedings of the 4th Decennial Symposium